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Program 11 Experimental and Computational Study of the Viscoplastic Response of High Temperature Structures

E. A. Thornton, M. F. Coyle and J. D. Kolenski

Objectives

The basic objectives of the research program are to: (1) investigate thermoviscoplastic (TVP) response of thin panels subject to intense local heating, and (2) evaluate finite element thermal-structural analyses with TVP constitutive models by comparison with experimental data.

Experimental and Computational Studies of Thermoviscoplastic Panels

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Marshall Coyle
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Abstract

The presentation will describe the first nine months of experimental and computational studies of the thermal-structural behavior of thin panels subjected to localized heating. Initial experimental studies have focused on developing an experimental set-up with well-defined thermal-structural boundary conditions. Preliminary tests with a "Heldenfels" panel have demonstrated out of plane bending (thermal buckling) due to panel initial imperfections. Initial computational studies have focused on: (1) validation of a thermoviscoplastic code to predict thermal stresses in the unbuckled panel, and (2) investigating in-plane stresses for test panels under transient thermal loading. Plans for future research are described in the presentation.

EXPERIMENTAL AND COMPUTATIONAL STUDIES OF THERMOVISCOPLASTIC PANELS

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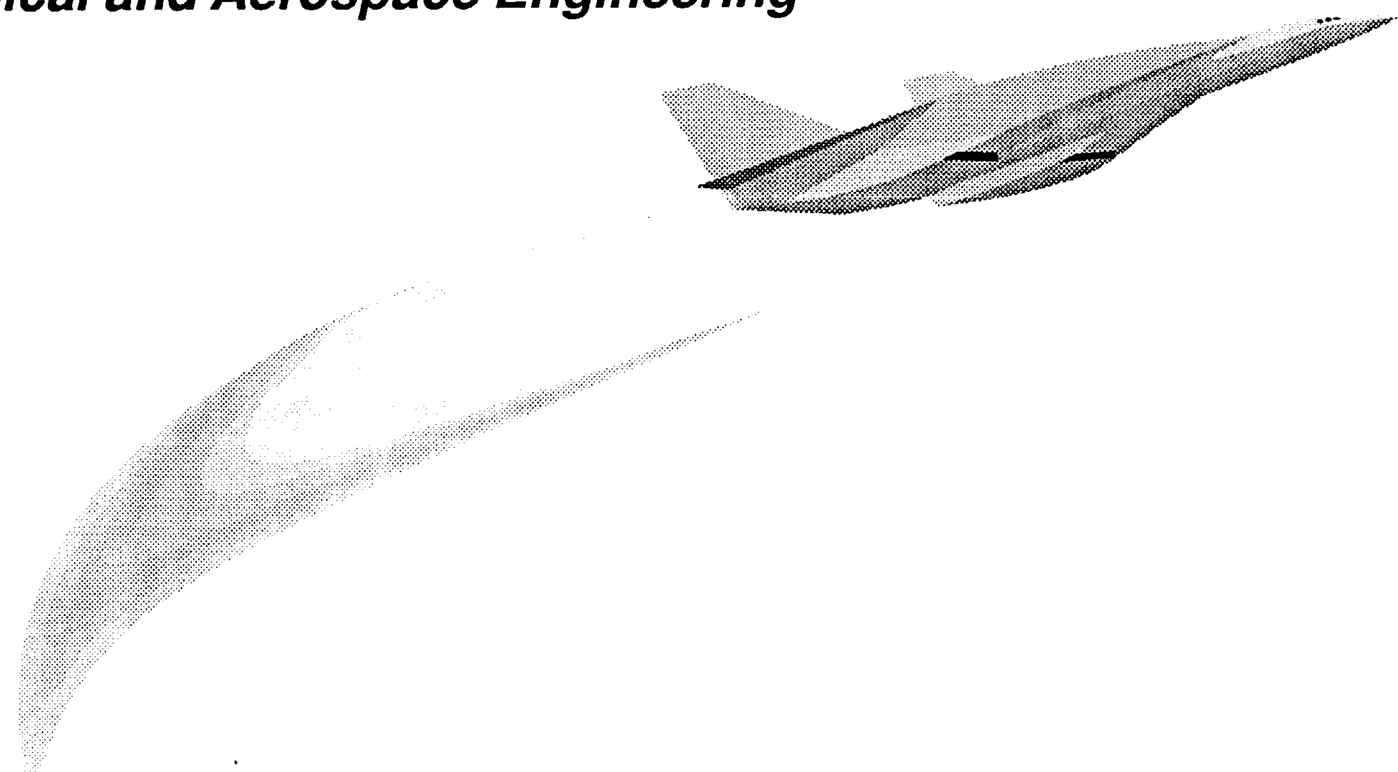
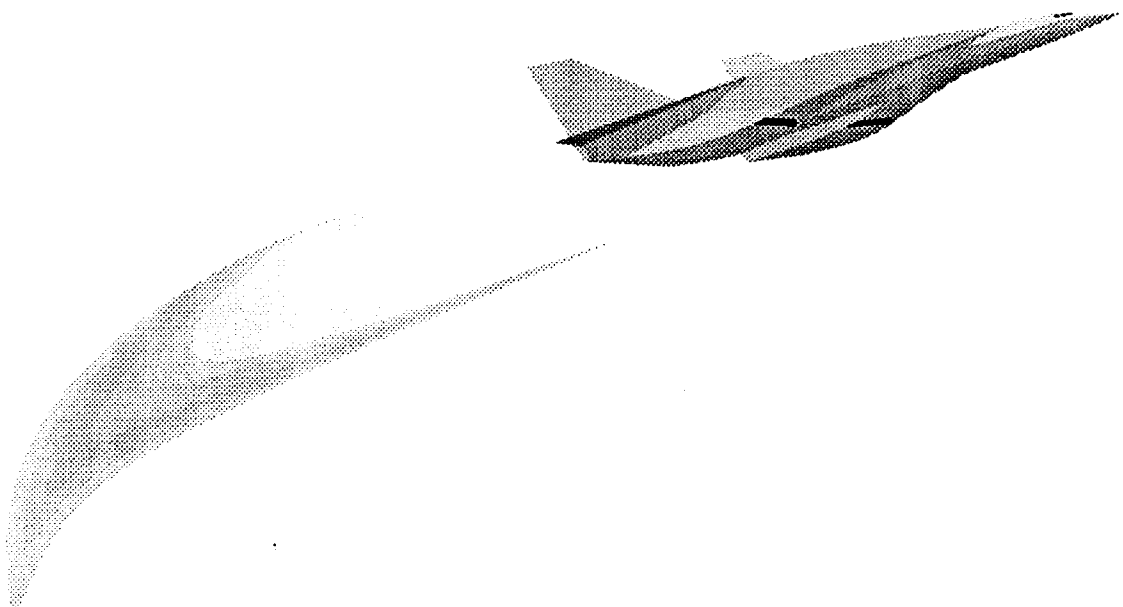
Mechanical and Aerospace Engineering

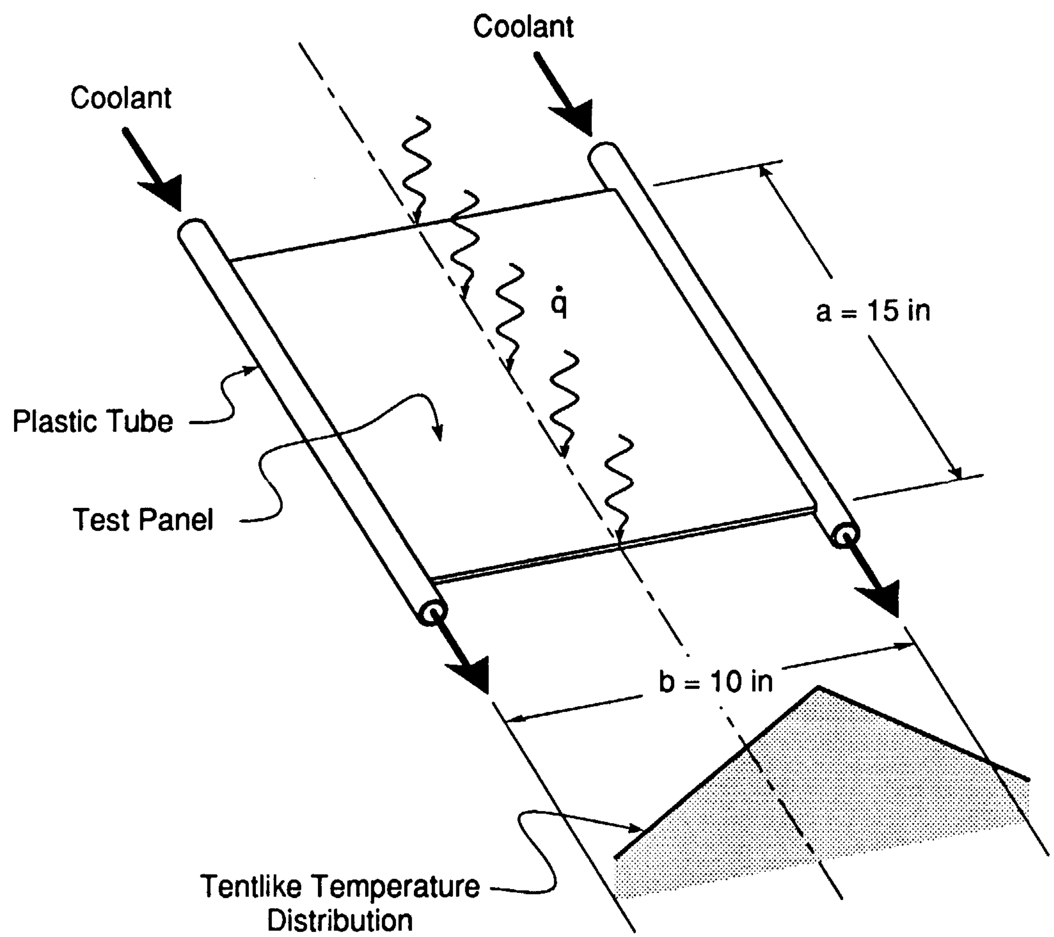


RESEARCH OBJECTIVES

- Investigate Thermoviscoplastic (TVP) response of thin panels subject to intense local heating.
- Evaluate finite element Thermal-Structural analyses with unified TVP constitutive models by comparison with experimental data.



HELDENFELS PROBLEM



EXPERIMENTAL PROGRAM

PHASE 1 - UNSUPPORTED "HELDENFELS" PANEL (304 SS)

OBJECTIVES:

- Evaluate Nichrome Wire Heating Technique
- Check out Coolant System
- Observe Qualitative Behavior of Panel

PHASE 2 - ENCLOSED SUPPORTED PANEL

OBJECTIVES:

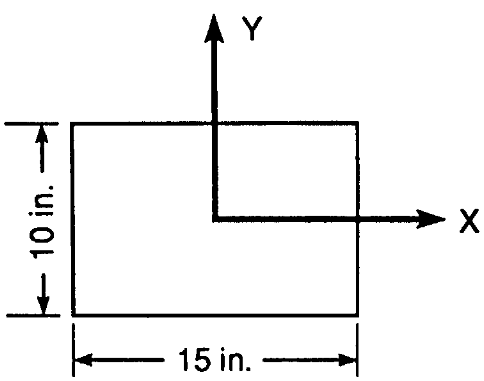
- Investigate Alternative Insulation Schemes
- Obtain Thermal Data
- Investigate Support System Design
- Install Data Acquisition System

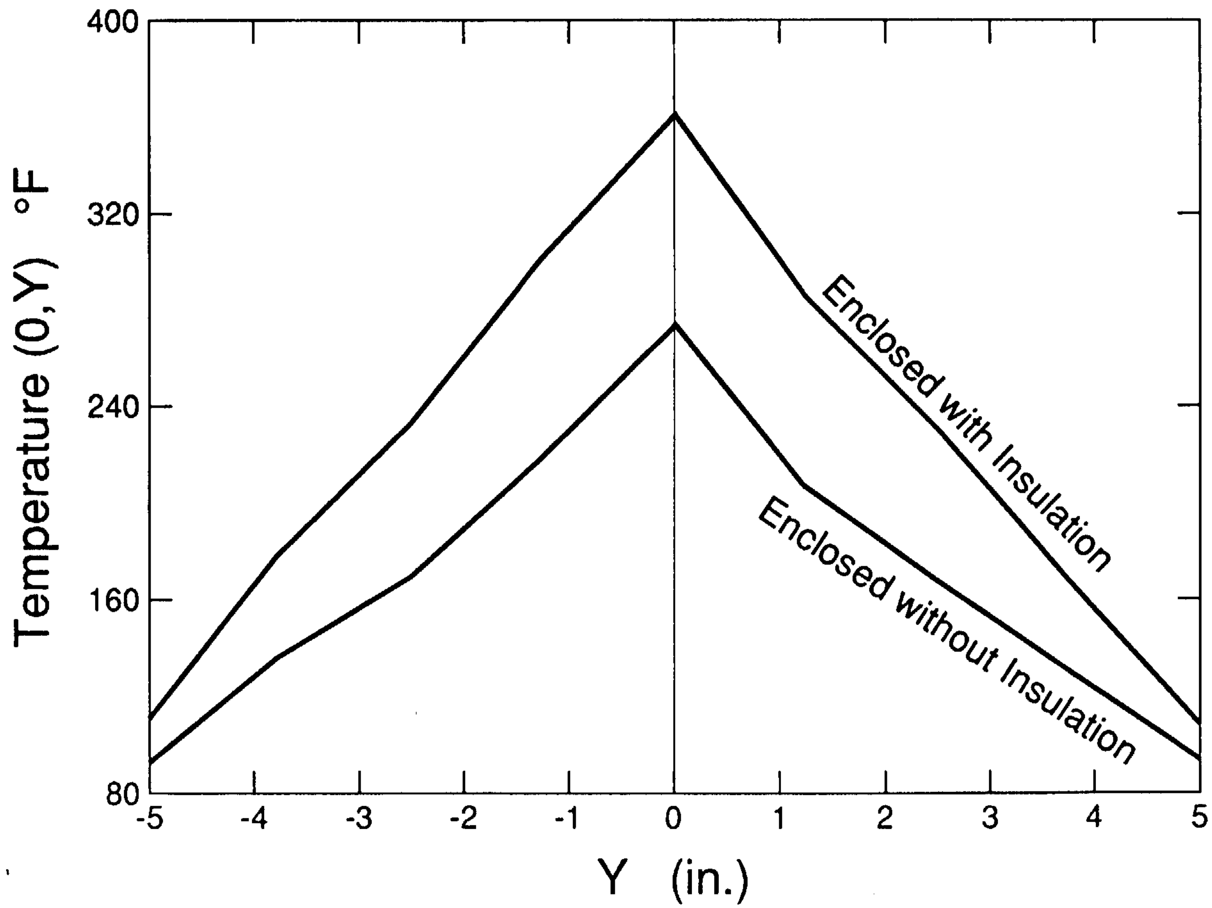
Color Slides Will Show The Experiments

INITIAL EXPERIMENTAL RESULTS

- WIRE HEATING
  - -Produces up to 20W/in.
  - -Limited to Panel Temperatures of 500° F by RTV
- CLOSED-LOOP CHILL WATER COOLING SYSTEM DESIRABLE
- PANEL DEMONSTRATES SIGNIFICANT BENDING
  - -Thickness Delta Temperature Less than 3° F
  - -Thermal Buckling due to Panel Initial Deflections
- HEAVY INSULATION REQUIRED FOR LINEAR TEMPERATURES
- TO TEST BARE PANEL, NEED TO MINIMIZE FREE CONVECTION

EXPERIMENTAL TEMPERATURES FOR TEST PANEL

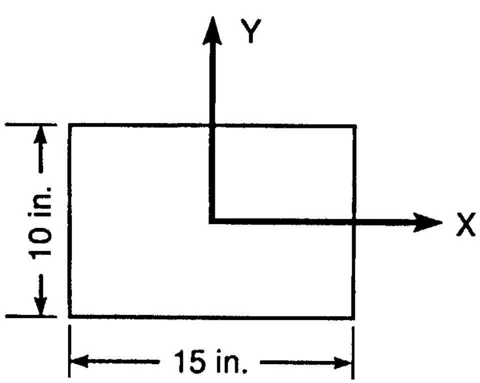


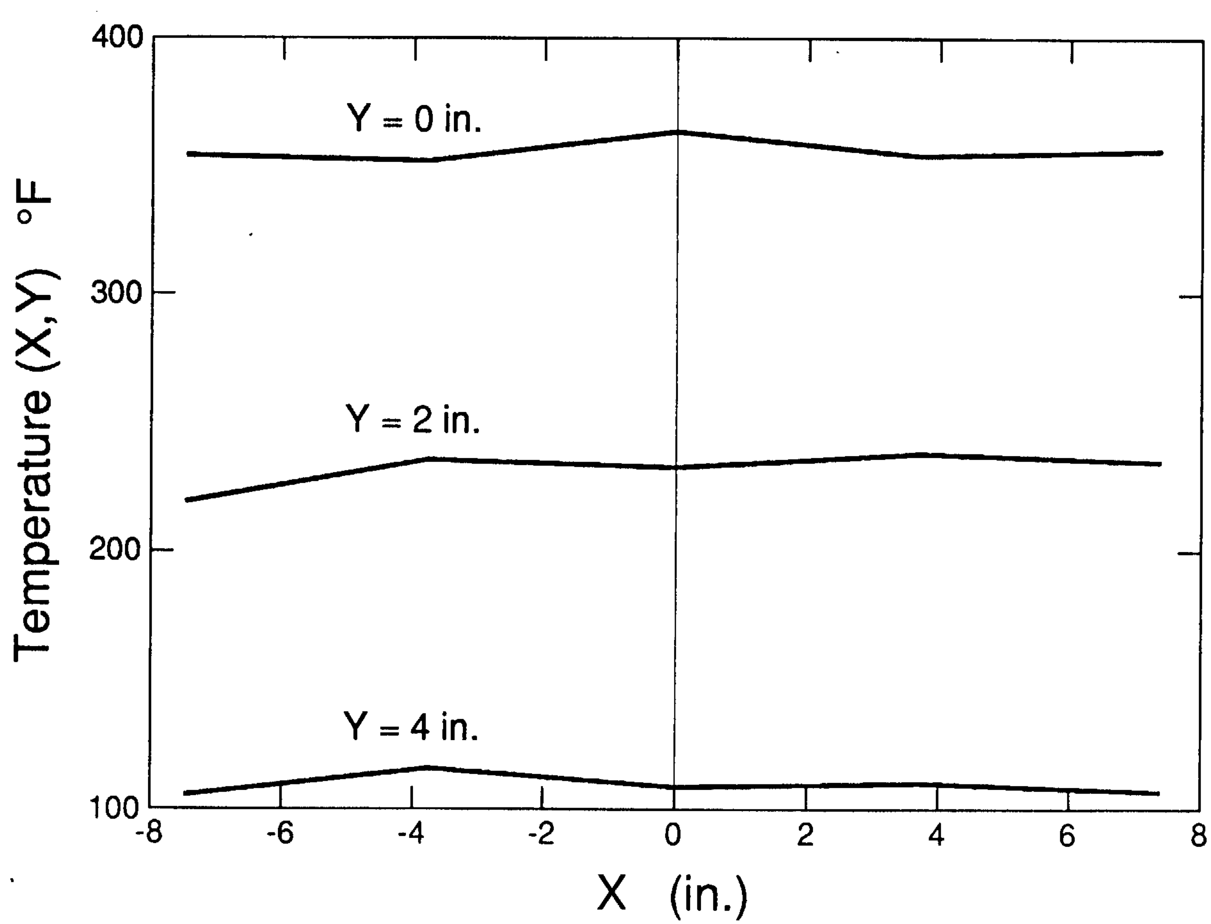


FUTURE RESEARCH PLANS

- MEASURE INITIAL DEFORMATIONS OF HASTELLOY-X
- INSTALL AND EVALUATE CHILL-WATER COOLANT SYSTEM
- INSTRUMENT HASTELLOY-X TEST PANEL
- BEGIN TESTS OF HASTELLOY-X PANEL

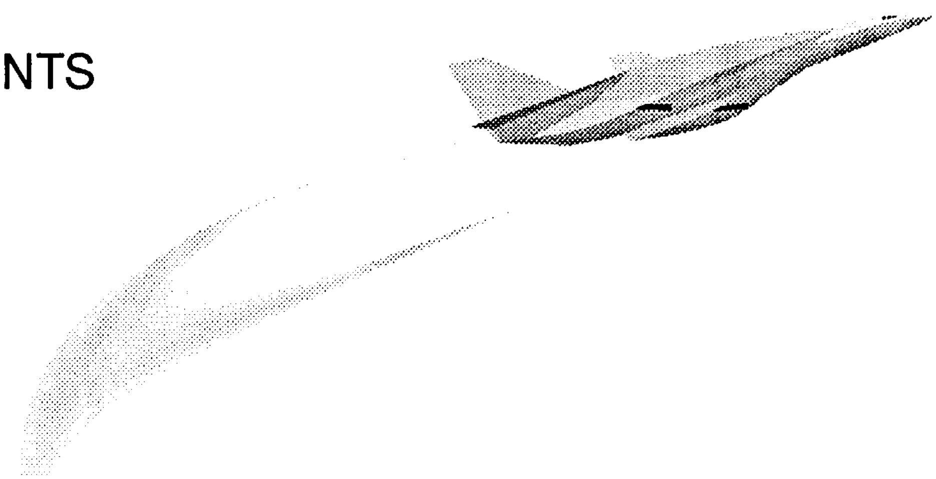
EXPERIMENTAL TEMPERATURES FOR INSULATED TEST PANEL



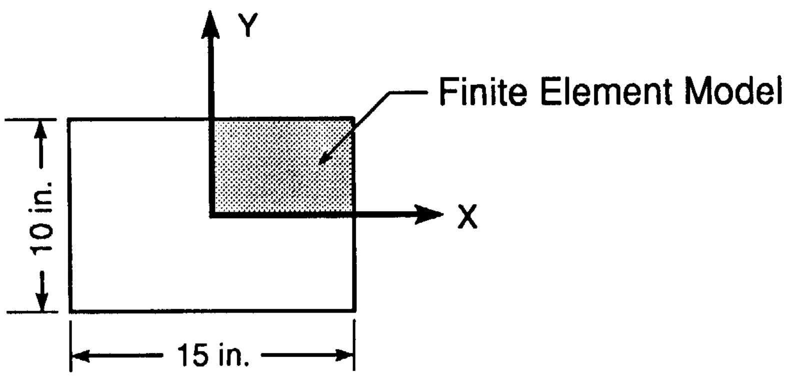


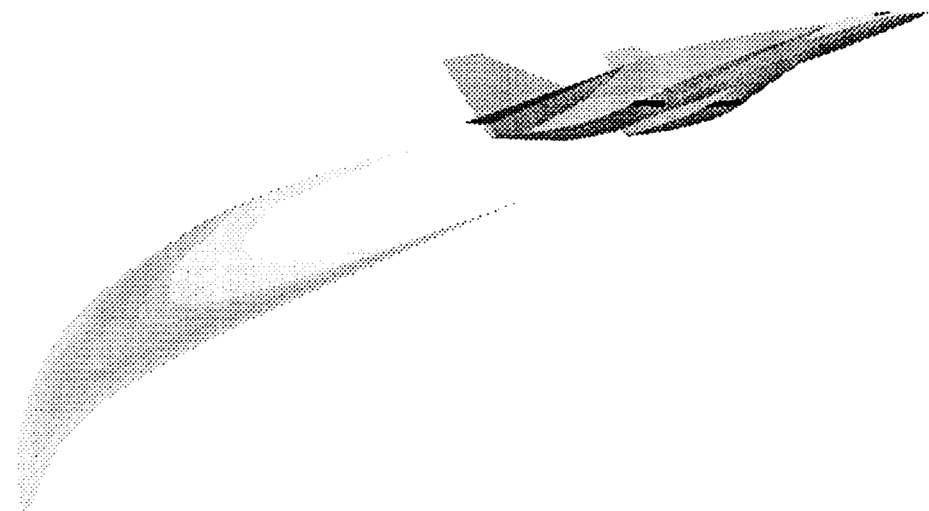
FINITE ELEMENT THERMOVISCOPLASTIC ANALYSIS

- ASSUMES QUASI-STATIC THERMAL STRESS BEHAVIOR
  - -Neglects Thermal-Mechanical Coupling in Energy Equation
  - -Neglects Inertia Forces in Equations of Motion
- ASSUMES PLANE STRESS
- USES BODNER-PARTOM CONSTITUTIVE MODEL
- IMPLEMENTS EQUATIONS IN RATE FORM AND USES TIME-MARCHING ALGORITHM (REFERENCE 3)
- USE QUADRILATERAL ELEMENTS



FINITE ELEMENT ELASTIC VALIDATION ANALYSIS

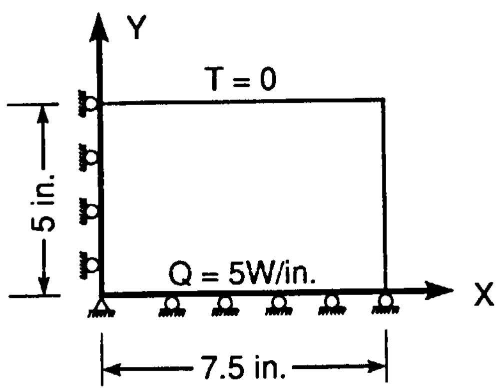




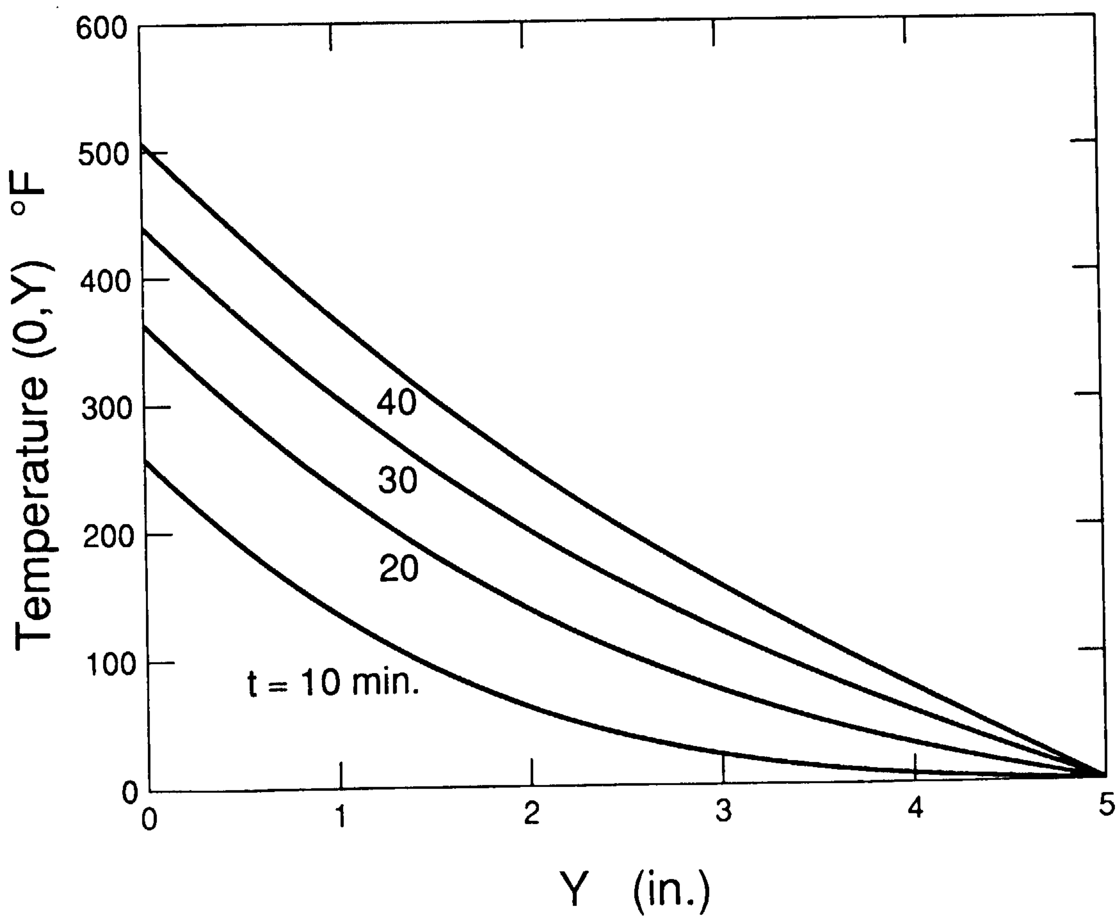
- USES 1D ANALYTICAL SOLUTION FOR T (Y,t)
- ASSUMES 1/4 SYMMETRY
- UNIFORM MESH - 176 nodes and 150 elements
- USES B1900 + Hf SUPERALLOY MATERIAL
- COMPARED RESULTS WITH COMMERCIAL *ANSYS* CODE

ELASTIC VALIDATION ANALYSIS

Boundary Conditions

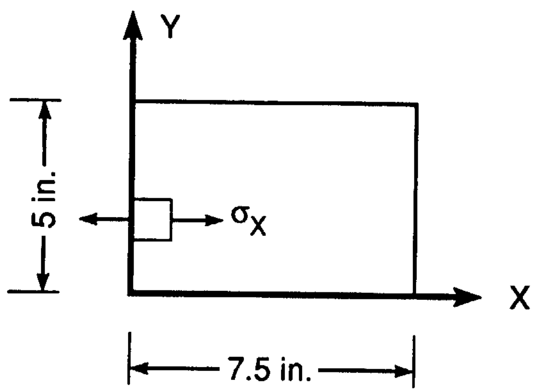


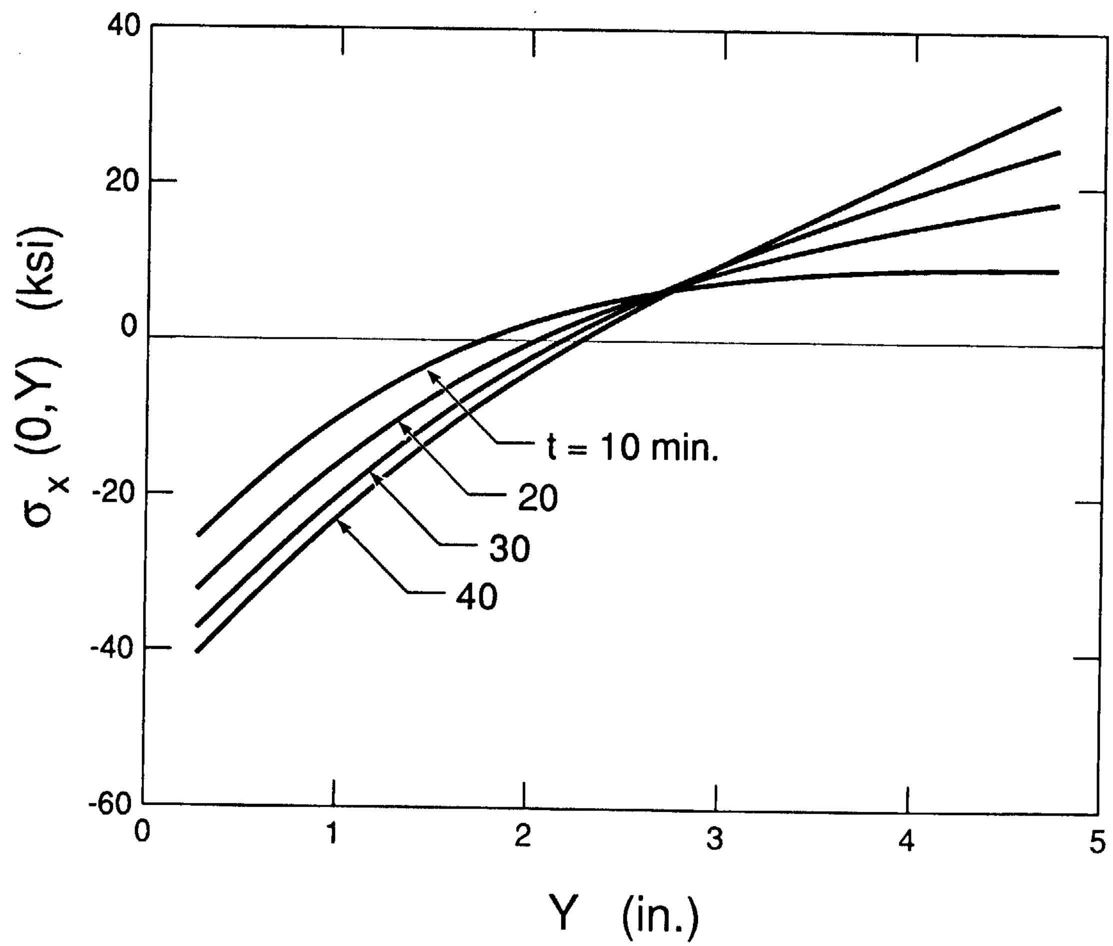
Analytical Solution



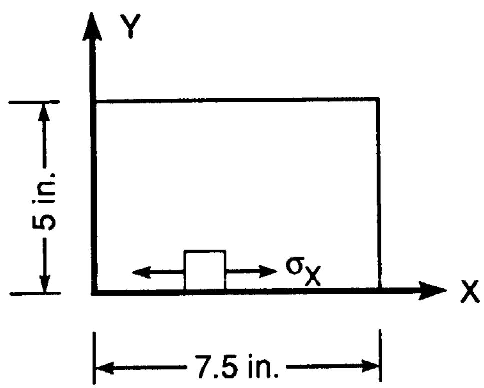
ELASTIC VALIDATION ANALYSIS

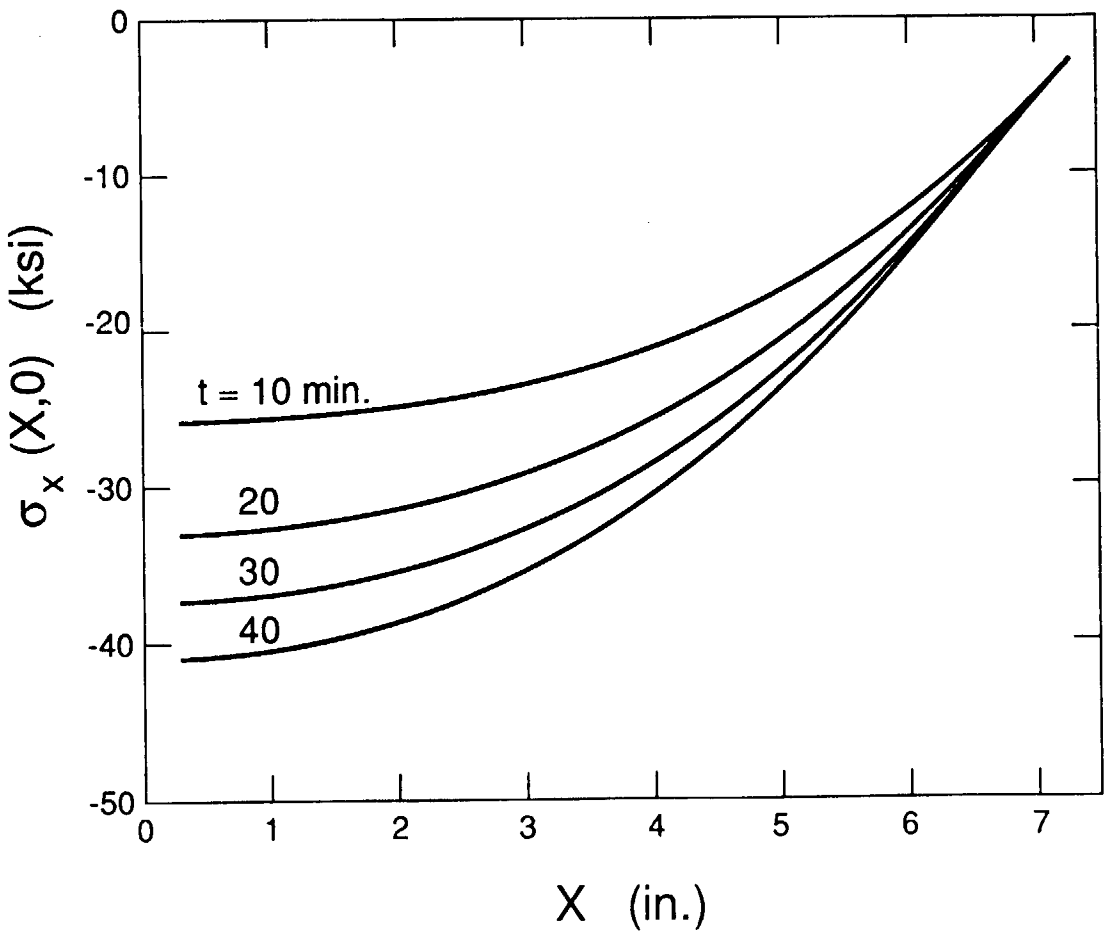
- Predicted Stresses Identical to ***ANSYS*** Results



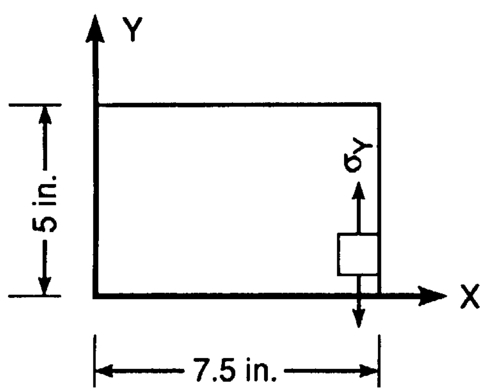


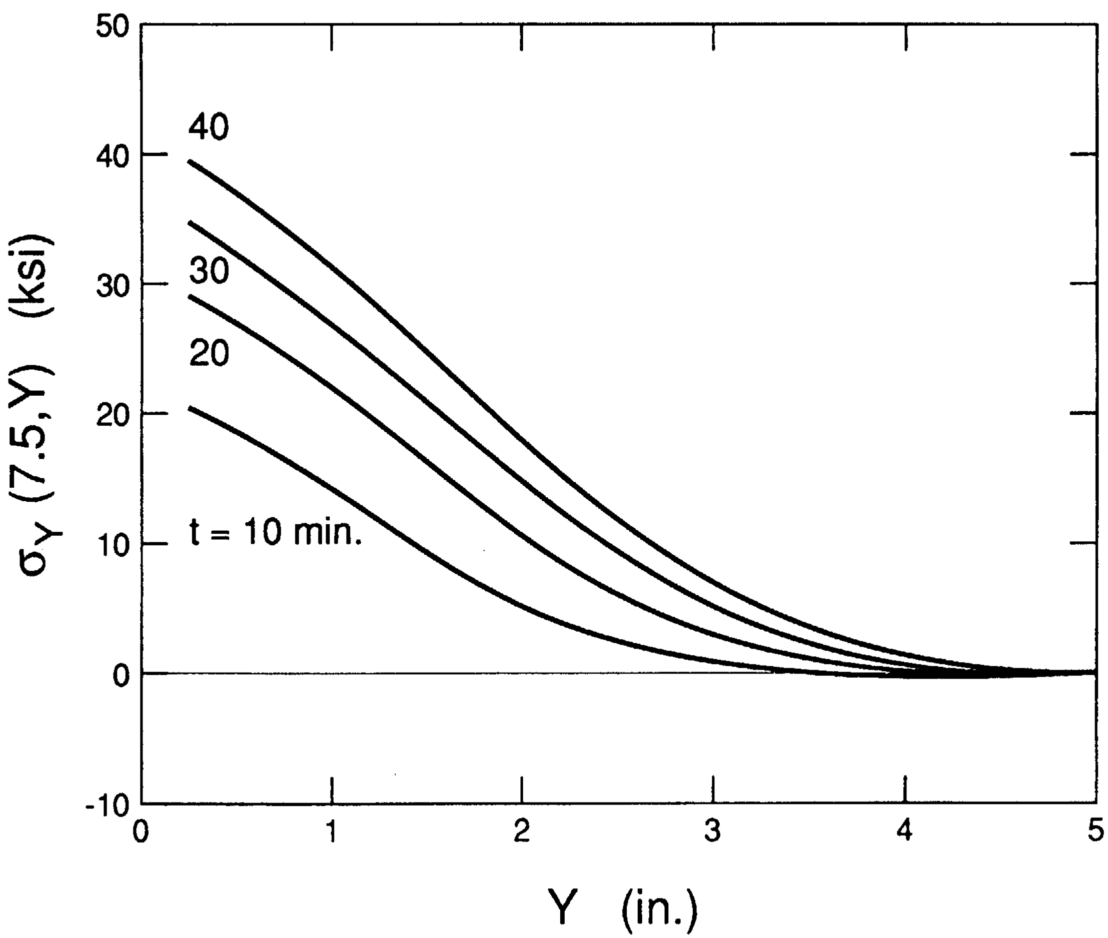
ELASTIC VALIDATION ANALYSIS



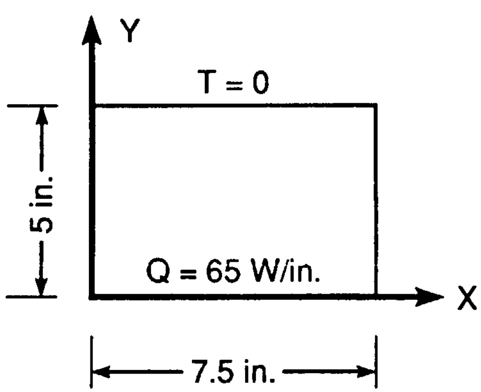


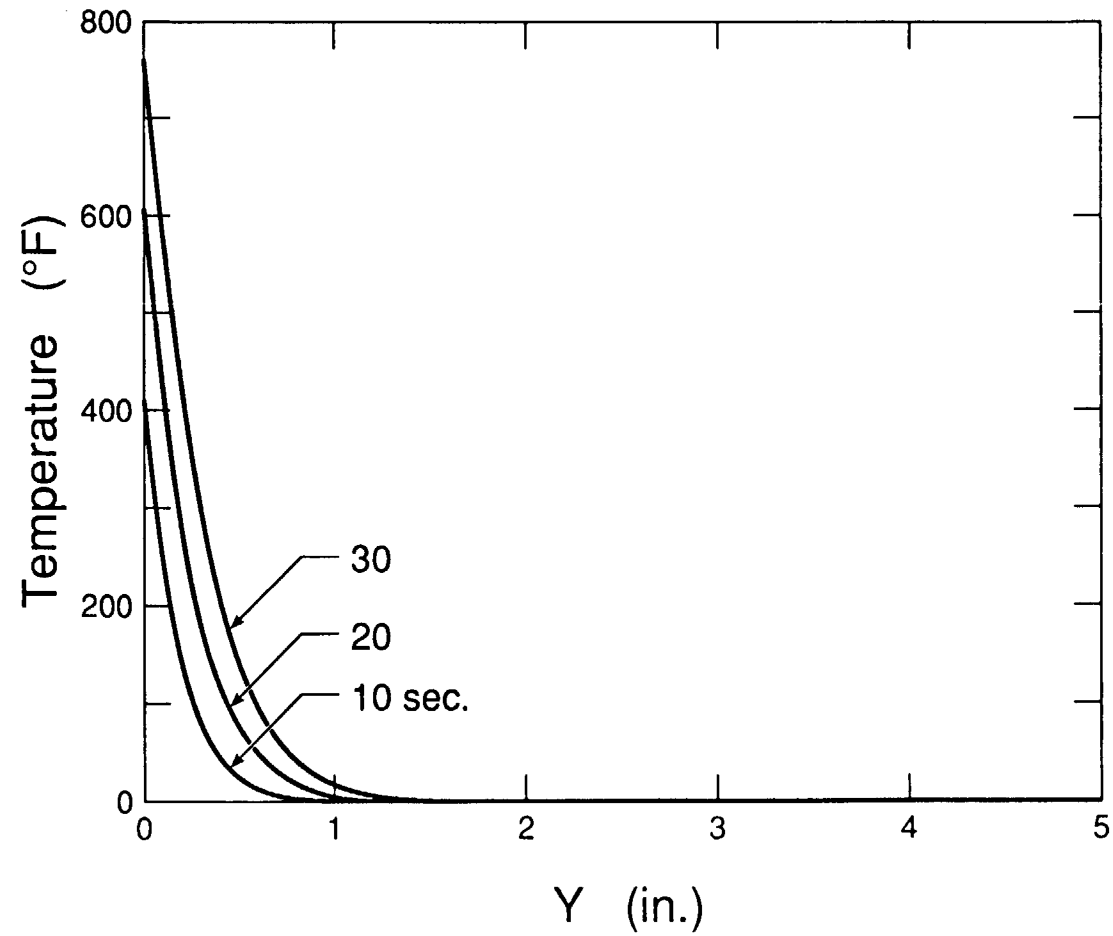
ELASTIC VALIDATION ANALYSIS



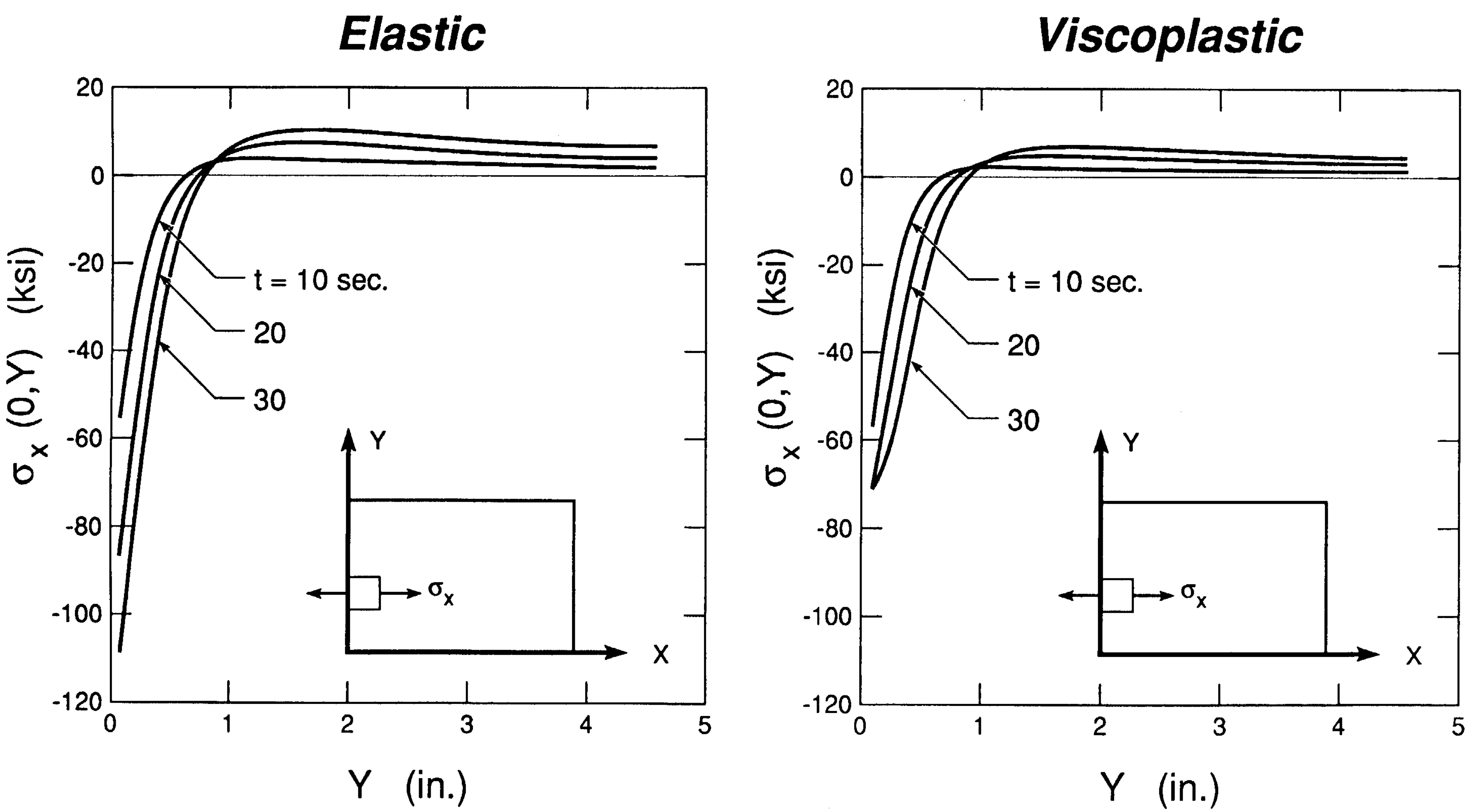


ELASTIC VS. VISCOPLASTIC RESPONSE FOR HIGH HEATING

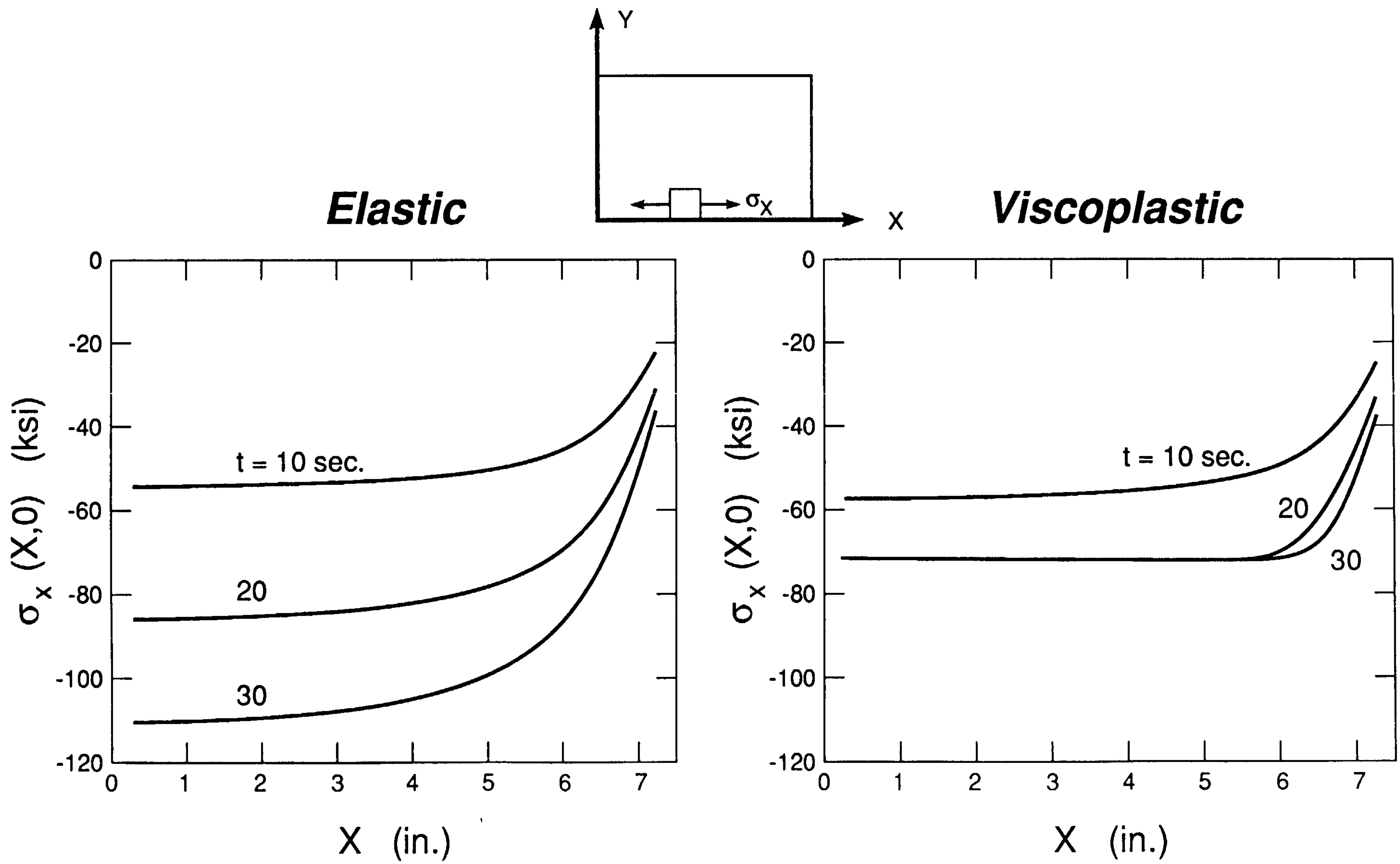




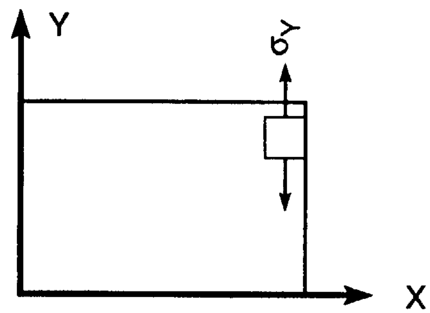
ELASTIC VS. VISCOPLASTIC RESPONSE



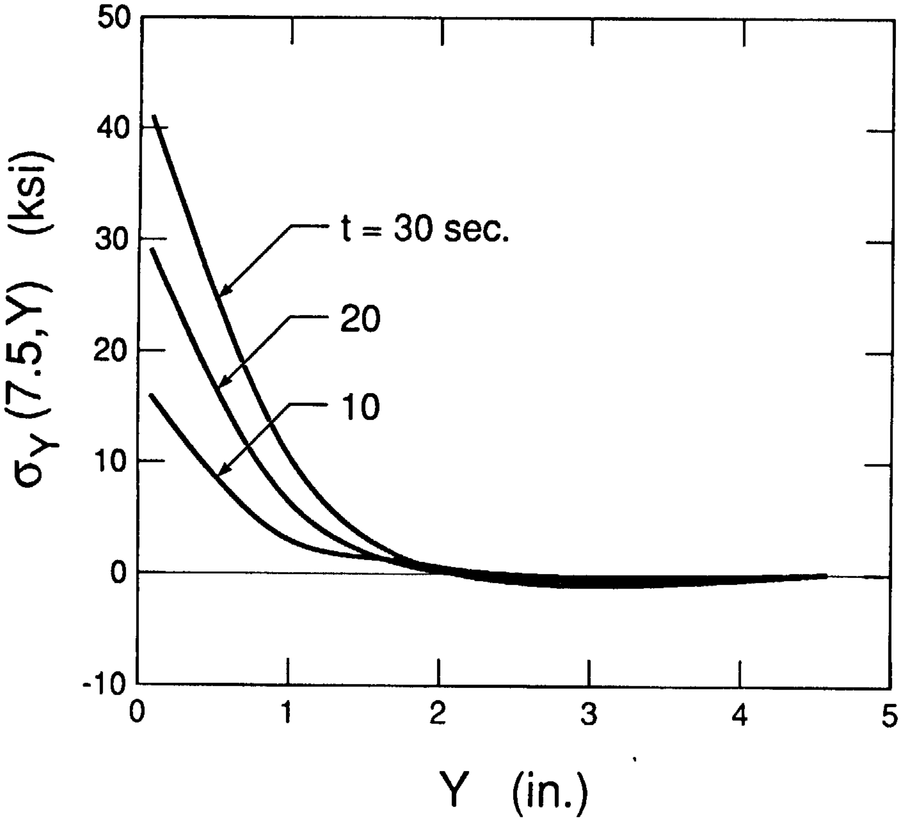
ELASTIC VS. VISCOPLASTIC RESPONSE



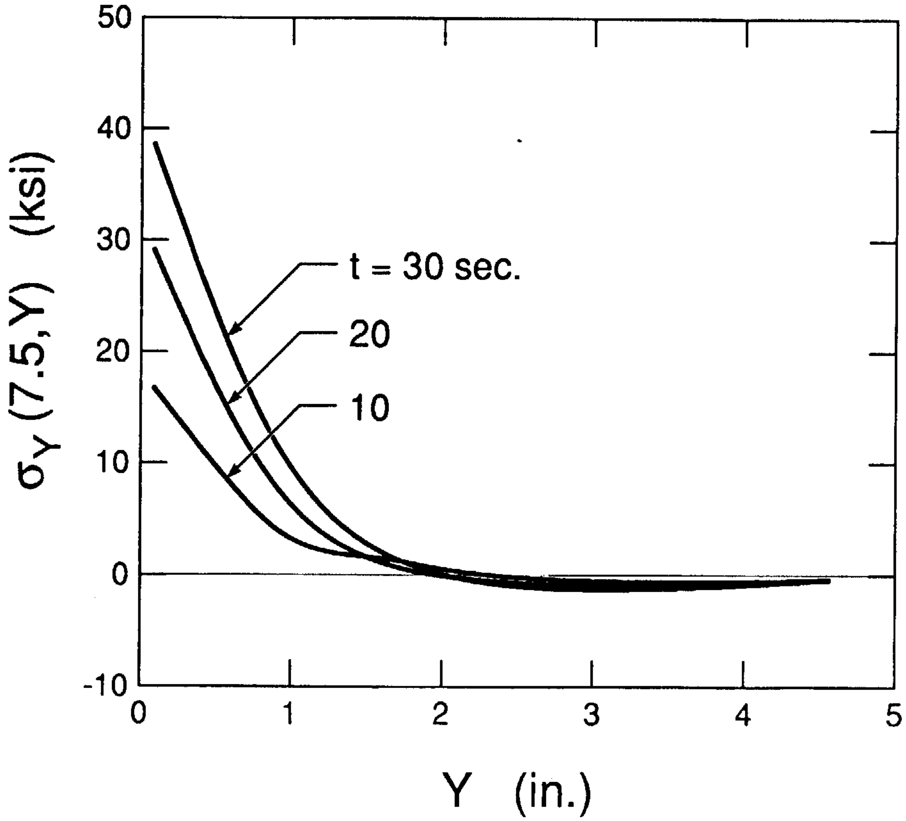
ELASTIC VS. VISCOPLASTIC RESPONSE



Elastic



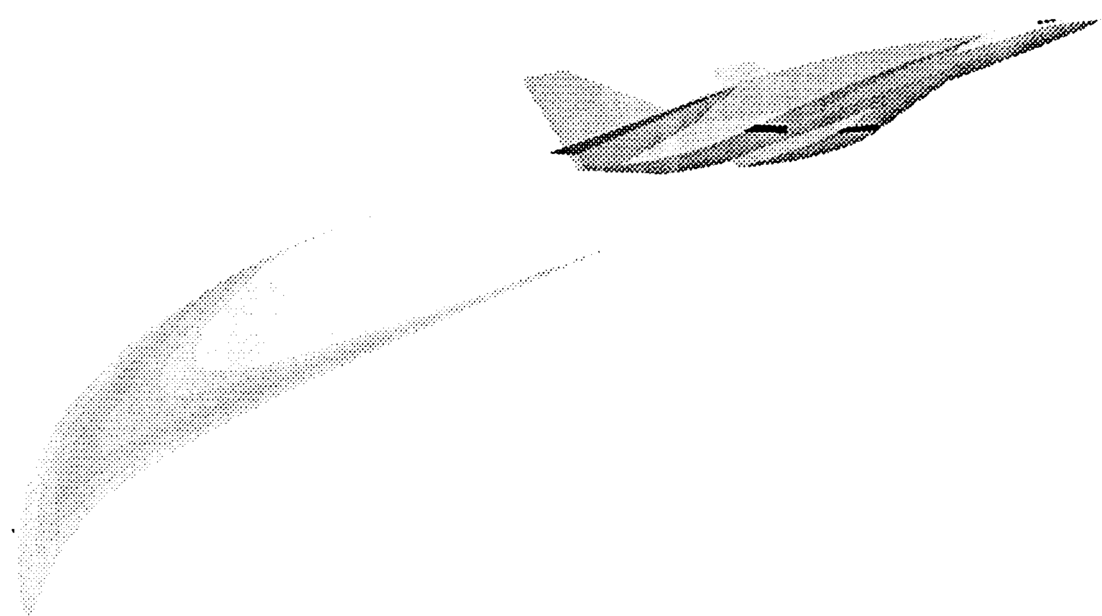
Viscoplastic



FUTURE RESEARCH

COMPUTATIONAL:

- INVESTIGATE QUASI-STATIC ASSUMPTION FOR TVP
- BEGIN DEVELOPMENT OF LARGE DEFLECTION, TVP, PLATE BENDING ANALYSIS



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2. Gossard, Myron L., Seide, Paul and Roberts, William M.: "Thermal Buckling of Plates," NACA TN 2771, 1952.

3. Thornton, Earl A., Oden, J. Tinsley, Tworzydlo, W. Woytek and Youn, Sung-Kie: "Thermo-Viscoplastic Analysis of Hypersonic Structures Subjected to Severe Aerodynamic Heating," AIAA 89-1226, 1989. To appear in the Journal of Aircraft.

APPENDIX I: GRANT PUBLICATIONS

1. R.P. Gangloff, "Hydrogen Effects on Fatigue Crack Propagation in Metals", in Proceedings Conference on Advanced Earth-To-Orbit Propulsion Technology, R.J. Richmond and S.T. Wu, eds., NASA, Marshall Space Flight Center, Huntsville, Alabama, in press (1990).[1]

2. R.P. Gangloff, R.S. Piascik, D.L. Dicus and J.C. Newman, "Fatigue Crack Propagation in Aerospace Aluminum Alloys", Proceedings 17th ICAS Congress, Royal Aeronautical Society, London, UK, in press (1990).

3. R.G. Buchheit, J.P. Moran and G.E. Stoner, "The Role of Hydrolysis in the Crevice Corrosion of Aluminum-Lithium-Copper Alloys", Corrosion '90, Paper No. 93, NACE, Houston, TX (1990).

4. C.T. Herakovich, J. Aboudi and J.L. Beuth, Jr., "A Micromechanical Composite Yield Model Accounting for Residual Stresses", Proceedings, IUTAM Symposium on Inelastic Behavior of Composite Materials, RPI, Troy, NY, May (1990).

5. J. Aboudi and M.-J. Pindera, "Matrix Mean-Field and Local-Field Approaches in the Analysis of Metal Matrix Composites", Proceedings, IUTAM Symposium on Inelastic Behavior of Composite Materials, RPI, Troy, NY, May (1990).

[1] This research was predominantly supported by R.G. Forman of the L.B. Johnson Space Flight Center, Houston, Texas.

APPENDIX II: GRANT PRESENTATIONS

1. R.P. Gangloff, "Environmental Fatigue Crack Propagation in Al-Li-Cu Alloys", Department of Materials Science, University of California, Berkeley, CA, April, 1990.

2. R.S. Piascik and R.P. Gangloff, "Environmental Fatigue Crack Propagation in Al-Li-Cu Alloys", Corrosion/90, NACE, Las Vegas, NV, April, 1990.

3. R.P. Gangloff, "Hydrogen Effects on Fatigue Crack Propagation in Metals", Conference on Advanced Earth-To-Orbit Propulsion Technology, Huntsville, AL, May, 1990.

4. R.S. Piascik, "Mechanisms of Corrosion Fatigue Crack Propagation: Al-Li-Cu System", Advanced Aerospace Materials and Processes Conference, Long Beach, CA, May, 1990.

5. D.B. Gundel and F.E. Wawner, " Investigation of the Reaction Kinetics Between SiC Fibers and Selectively Alloyed Titanium Matrices", 14th Annual Conference on composite Materials and Advanced Structures, Cocoa Beach, FL, January, 1990.

6. F.E. Wawner and D.B. Gundel, "Investigation of Reaction Kinetics and Interfacial Phase Formation in Ti_3Al + Nb Composites", Titanium Aluminide Composite Workshop, Orlando, FL, May, 1990.

7. D.B. Gundel and F.E. Wawner, "Investigation of the REaction Kinetics Between SiC Fibers and Selectively Alloyed Titanium Matrix Composites", Advanced Aerospace Materials and Processes Conference, Long Beach, CA, May, 1990.

8. R.G. Buchheit, J.P. Moran and G.E. Stoner, "The Role of Hydrolysis in the Crevice Corrosion of Aluminum-Lithium-Copper Alloys", Corrosion/90, NACE, Las Vegas, NV, April, 1990.

9. J.P. Moran, R.G. Buchheit and G.E. Stoner, "The Effects of Bulk and Local Solution Chemistries on the SCC Behavior of Alloy 2090 (Al-Li-Cu)", Research Symposium, Corrosion/90, NACE, Las Vegas, NV, April, 1990.

APPENDIX III: ABSTRACTS OF GRANT PUBLICATIONS

HYDROGEN ENVIRONMENT ENHANCED FATIGUE CRACK PROPAGATION IN METALS[1]

RICHARD P. GANGLOFF[2]

Abstract

Fracture mechanics-based methods for damage tolerant fatigue life prediction do not adequately describe the deleterious effect of the surrounding environment. Such analyses are complicated by the time dependence of crack growth rates (da/dN), by a multitude of important variables and by compromises of ΔK similitude. Gases and electrolytes which produce hydrogen by reactions with crack surfaces enhance da/dN in aerospace iron, aluminum and nickel-based alloys. Environment causes time-dependent cracking above the sustained load threshold (K_{ISCC}) and cycle-time-dependent cracking below K_{ISCC} where cyclic deformation is uniquely damaging. Crack growth in superalloys in elevated temperature oxidizing air is phenomenologically similar to low temperature hydrogen environment fatigue. The magnitude of the hydrogen environment effect on da/dN depends on environment activity (gas pressure, temperature and electrode potential); ΔK, waveform and mean level; loading frequency and hold time; and alloy composition, microstructure and σ_{ys}. Models for da/dN-ΔK are developed based on linear superposition, empirical curve fitting, and chemical damage mechanisms. With additional cited research, hydrogen effects can be incorporated into existing fatigue life prediction codes such as NASA FLAGRO.

Introduction

The fracture mechanics approach to damage tolerant control of fatigue crack propagation employs laboratory data on crack growth rate (da/dN) versus stress intensity range ($\Delta K = K_{max} - K_{min}$) for quantitative predictions of component life through the similitude concept suggested by Paris and coworkers[1]. Over the past 15 years, the method has been advanced to account for near-threshold fatigue cracking[2], small crack effects[3], crack closure[4], spectrum loading[5] and the behavior of anisotropic advanced materials[6]. This method has been successfully incorporated into computerized life prediction codes for aerospace components[7-10]; however such work has focused on fatigue in moist air.

Environment, particularly when capable of producing atomic hydrogen through reactions with a metal, deleteriously affects rates of fatigue crack propagation in most structural alloys[11-18]. The application of fracture mechanics to environmental fatigue crack propagation has progressed over the past 25 years[19]. Notable advances include: (a) the demonstration of ΔK similitude[20], (b) developments of experimental methods[21], (c) characterizations of da/dN-ΔK[11], (d) identification of crack closure and small crack-environment interactions[2,3], (e) scientific studies of mechanisms[19] and (f) life prediction methods for energy systems[22,23]. Hydrogen environment effects have not, however, been systematically incorporated into life prediction methods for aerospace components.

Two factors hinder quantitative life prediction to control environmental fatigue crack propagation

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[1]This work is conducted in collaboration with R.G. Forman of the L.B. Johnson Space Flight Center under contract LESC-SOW-N-2584.

[2]Professor, Department of Materials Science, School of Engineering and Applied Science, Thornton Hall, University of Virginia, Charlottesville, VA, 22903.

In: Proceedings Conference on Advanced Earth-To-Orbit Propulsion Technology, R.J. Richmond and S.T. Wu, eds., NASA, Marshall Space Flight Center, Huntsville, Alabama, In press (1990).

FATIGUE CRACK PROPAGATION IN AEROSPACE ALUMINUM ALLOYS

R.P. Gangloff[1], R.S. Piascik[2], D.L. Dicus[3] and J.C. Newman, Jr.[4]

Abstract

This paper reviews fracture mechanics based, damage tolerant characterizations and predictions of fatigue crack growth in aerospace aluminum alloys. The results of laboratory experimentation and modeling are summarized in the areas of: (a) fatigue crack closure, (b) the wide range crack growth rate response of conventional aluminum alloys, (c) the fatigue behavior of advanced monolithic aluminum alloys and metal matrix composites, (d) the short crack problem, (e) environmental fatigue and (f) variable amplitude loading. Remaining uncertainties and necessary research are identified. This work provides a foundation for the development of fatigue resistant alloys and composites, next generation life prediction codes for new structural designs and extreme environments, and to counter the problem of aging components.

I. Introduction

The fracture mechanics approach to fatigue crack propagation quantitatively couples laboratory studies on alloy performance and fatigue mechanisms with damage tolerant life prediction methods through the concept of growth rate similitude. This method, illustrated in Figure 1, is traceable to the seminal results of Paris and coworkers for the case of moist air environments[1] and is outlined in current textbooks[2]. Subcritical fatigue crack propagation is measured in precracked laboratory specimens according to standardized methods[3]. Crack length (a) versus load cycles (N) data are analyzed to yield a material property; averaged fatigue crack growth rate (da/dN) as a function of the applied stress intensity range, ΔK. ΔK is the difference between maximum (K_{max}) and minimum (K_{min}) stress intensity values during a load cycle. Paris experimentally demonstrated the principle of similitude; that is, equal fatigue crack growth rates are produced for equal applied stress intensity ranges, independent of load, crack size and component or specimen geometry[1]. Wei and coworkers extended this concept to describe corrosion fatigue crack propagation in aggressive gas and liquid environments[4].

The similitude principle enables an integration of laboratory da/dN-ΔK data to predict component fatigue

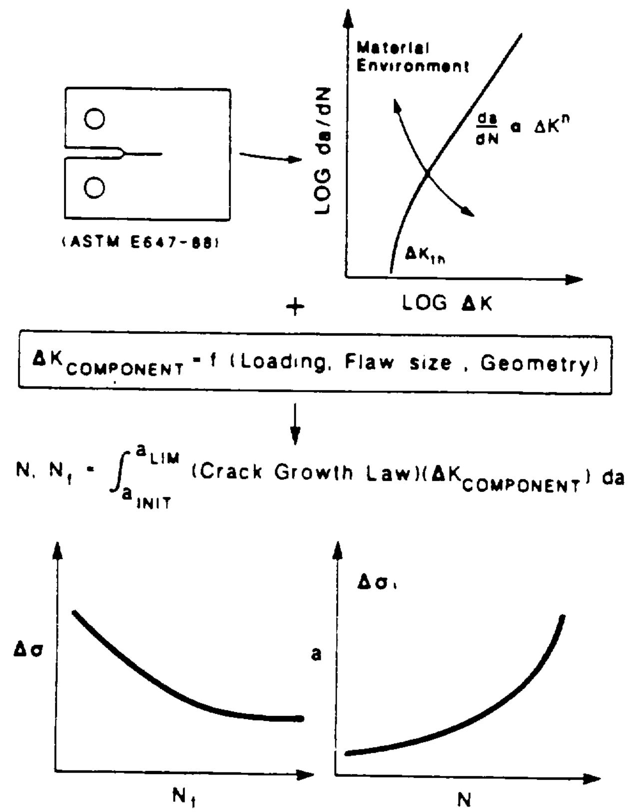

Figure 1. *Fracture mechanics approach to fatigue crack growth: material characterization and component life prediction.*

behavior, in terms of either applied stress range ($\Delta\sigma$) versus total life (N_f) or crack length (a) versus load cycles (N), for any initial defect size and component configuration. These calculations require component loading and stress analyses, initial crack size and shape, and a component stress intensity solution. This method has been developed for complex structural applications in the energy, petrochemical and

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[3] Metallic Materials Branch, Materials Division, NASA Langley Research Center, Hampton, VA, 23665.

[4] Mechanics of Materials Branch, Materials Division, NASA Langley Research Center, Hampton, VA, 23665.

IN: *Proceedings 17th ICAS Congress, Royal Aeronautical Society, London, UK, in press (1990).*

THE ROLE OF HYDROLYSIS IN THE CREVICE CORROSION OF ALUMINUM-LITHIUM-COPPER ALLOYS

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CHarlottesville, VA 22901

ABSTRACT

The hydrolytic behavior of cations plays an important role in the crevice corrosion of aluminum and its alloys. Hydrolysis equilibrium reactions can either consume or produce H^+ thereby altering pH. An external cathode electrolytically coupled to a crevice can also influence the pH developed in a crevice. In this study, simulated crevice experiments were performed with pure aluminum, solution heat treated (SHT) Al-3Li and SHT Al-3Cu to determine the effects of Al^{3+}, Li^+ and Cu^{2+} hydrolysis on steady state pH. Simulated crevice experiments were carried out with aerated bulk solutions, deaerated bulk solutions and with no bulk solution to determine the effect of a remote cathode on the steady state pH response. The pH response was interpreted in terms of distribution diagrams constructed from formation quotients and mass action equations for the appropriate hydrolysis products. Finally, the results of the above experiments were used to assess the roles of hydrolysis and the external cathode in determining the steady state pH measured in the ternary alloy Al-3Cu-2Li (AA 2090). In all experiments crevice acidification occurred when the bulk solution was aerated. When the bulk solution was deaerated or when no bulk solution was present a mildly alkaline crevice pH developed. Analysis of distribution diagrams shows that Al^{3+} hydrolysis can generate an acidic to neutral crevice solution. Lithium hydrolysis does not occur until a pH of 11 and is not an important process at the pH values observed here. However,lithium dissolution can assist in generating mild alkalinity. Evidence also suggests that some Cu^{2+} hydrolysis occurs contributing to the alkaline pH observed for isolated crevice in SHT Al-3Cu and SHT 2090.

A Micromechanical Composite Yield Model Accounting for Residual Stresses

C. T. Herakovich, J. Aboudi[1] and J. L. Beuth, Jr.
Civil Engineering Department
University of Virginia
Charlottesville, VA 22903

Abstract

An analytical micromechanical model is used to predict yielding in continuous-fiber unidirectional metal-matrix composite materials. The von Mises criterion is used to predict yielding of the composite matrix based on (1) the average stresses in the matrix, and (2) the largest of the average stresses in each of the modelled matrix subcells. Two-dimensional yield surfaces are generated under thermomechanical loading conditions for two metal matrix composites, boron/aluminum and silicon carbide/titanium. Results indicate that, depending on the material, temperature excursions typically experienced in processing may cause matrix yielding at zero far-field applied stress. The analysis shows that thermal stresses distort and shift the yield surface based upon subcell stresses. Thus the importance of micromechanics is demonstrated.

1. Introduction

The ability to use metal matrix composites at high temperatures is one of their important advantages over resin matrix composites. Since the metal matrix is an elastoplastic material, it appears that the prediction of the overall yield surface of the composite is a fundamental step toward the study of its behavior. Yielding of the composite is caused by the yielding of its metal matrix. The prediction of the initial yield surfaces of metal matrix composite in the absence of thermal effects was presented by Pindera and Aboudi (1988). It was shown that yield surfaces generated on the basis of the average matrix behavior generally underestimate initial yielding as compared with predictions based on local matrix stresses and that the results obtained on the basis of local matrix stresses correlate very well with finite element predictions of Dvorak et al (1973). The approach presented by Pindera and Aboudi (1988) is based on the micromechanical model of periodic array of fibers which was recently reviewed by Aboudi (1989). This micromechanical approach is analytical and requires minimal computational effort, while offering the ability to model generalized

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[1]Visiting from Tel Aviv University, Tel Aviv, Israel

Presented at the IUTAM Symposium, Troy, NY, May, 1990 and published in the proceedings of the IUTAM Symposium on Inelastic Behavior of Composite Materials.

Matrix Mean-Field and Local-Field Approaches

in the Analysis of Metal Matrix Composites

Jacob Aboudi[1]

Marek-Jerzy Pindera[2]

Abstract

A micromechanical investigation of the inelastic response of metal matrix composites analyzed by two different methodologies is presented. The first method is based on the mean stress field in the entire ductile matrix phase, while the second one is based on the local stress field. The present study is a continuation of a previous investigation in which a micromechanics model based on a periodic array of fibers was employed to generate yield surfaces of metal matrix composites using local and mean matrix stresses. In this paper, we extend the aforementioned analysis to the prediction of the inelastic stress-strain response of metal matrix composites subjected to different loading histories. Results for the overall elastoplastic response of the investigated metal matrix composites indicate that the mean-field approach may lead to significant deviations of the effective composite behavior as compared either to finite element results or measured data. The predictions of the effective composite response generated by the two approaches are compared with experimental and numerical data on unidirectional boron/aluminum and graphite/aluminum.

Introduction

In a previous investigation, Pindera and Aboudi (1988) discussed the use of average matrix stress in determining initial yield surfaces of metal matrix composites. Specifically, the micromechanics model proposed by Aboudi (1986) was employed to generate initial yield surfaces of unidirectional and multidirectional (cross-ply) boron/aluminum laminates under a variety of loading conditions using two different approaches. In the first approach, overall yielding of

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